

A NOVEL STRUCTURAL HEALTH MANAGEMENT APPROACH FOR STEEL BRIDGES

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Overview

- Problem Description
- Objectives
- Technical Approach
 - Team
- Technology Implementation
 - Fiber Bragg Grating
 - Acoustic Emission Sensors
 - Completed System
 - Data Acquisition and Analysis
- Next Steps
- Summary



Problem Description

- Corrosion of steel bridges remains a critical infrastructure concern
 - Corrosion of U.S. highway bridges costs economy \$8.3M annually *(Source: FHWA)*
 - 25% of U.S. bridges are structurally deficient or functionally obsolete *(Source: FHWA)*
 - 503 U.S. bridges failed over 11 year period (100 due to corrosion) *(Source: ERDC-CERL)*



Problem Description (cont.)

- Current method of monitoring - routine inspection – has limitations
 - Several techniques employed - visual, dye penetrant, ultrasonic, radiographic non-destructive testing methods
 - May not detect hidden cracks in built-up structures
 - Unable to determine if defect is actively growing



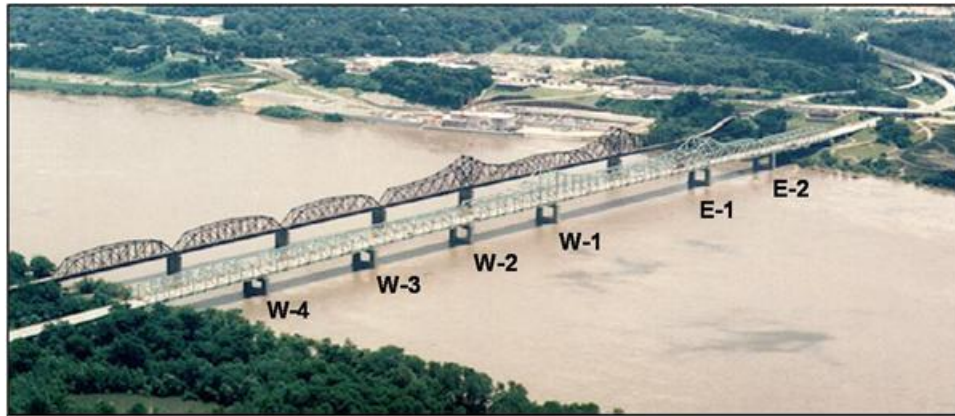
Objectives

- Demonstrate and validate state-of-the-art and emerging innovative technology approaches for remote structural health and corrosion degradation monitoring of steel bridges
- Employ system on two subject bridges to greatly reduce risk of catastrophic failure by providing advance warning of growing structural problems caused by corrosion/materials degradation



Objectives (cont.)

- Subject Bridge 1 – I-20 Bridge, Vicksburg, MS
 - Steel truss through deck
 - About 23,000 vehicles per day
 - Westward movement of bridge piers E-1 and E-2 on east side



Objectives (cont.)

- Subject Bridge 2 – Government Bridge, Rock Island, IL
 - Steel truss through deck
 - Built in 1893
 - About 10,300 vehicles per day (lower deck)
 - About five trains per day (upper deck)



Technical Approach

- Conduct structural assessment of subject bridges to determine optimal types and locations of sensors
- Integrate optical and other sensors into a novel structural health monitoring system specifically tailored to the subject bridges
- Design software that can not only collect data but can also interpret to provide early warning of areas of concern



Technical Approach (cont.)

- For the I-20 bridge, design and implement system utilizing:
 - Corrosion sensors – two types plus corrosion coupons
 - Accelerometers – modal response, monitor abnormal vibration characteristics
 - Strain gauges – monitor abnormal deflections
 - Tilt sensors
 - Deflection/displacement gauges – Monitor movement of piers and associated stress to structural members



Technical Approach (cont.)

- For the Government Bridge, design and implement system utilizing:
 - Corrosion sensors – two types plus corrosion coupons
 - Accelerometers – modal response, monitor abnormal vibration characteristics
 - Strain gauges – monitor abnormal deflections
 - Acoustic Emission sensors – monitor crack growth



Team Members

- U.S. Army Corps of Engineers, Engineer Research & Development Center Construction Engineering Research Laboratory (ERDC-CERL)
- Mandaree Enterprises Corporation (MEC)
- Concurrent Technologies Corporation (CTC)
- O'Donnell Consulting Engineers, Inc.
- Chandler Monitoring Systems, Inc.
 - Carlyle Consultants
 - Defense Science and Technology Office (DSTO), Australia
- Input from Office of the Secretary of Defense (OSD), other ERDC personnel, relevant Departments of Transportation (DOTs) and Directorates of Public Works (DPWs)

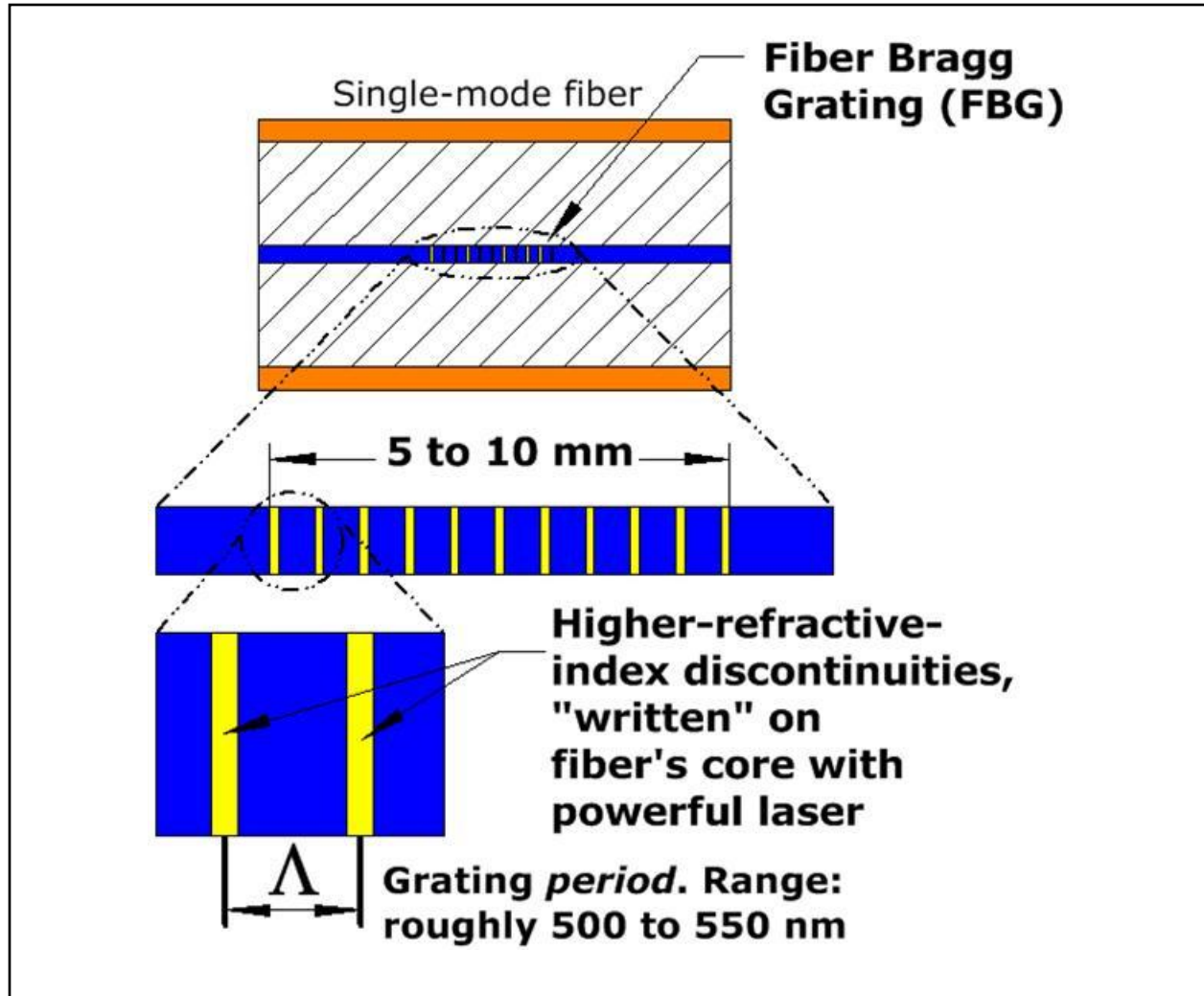


Technology Implementation

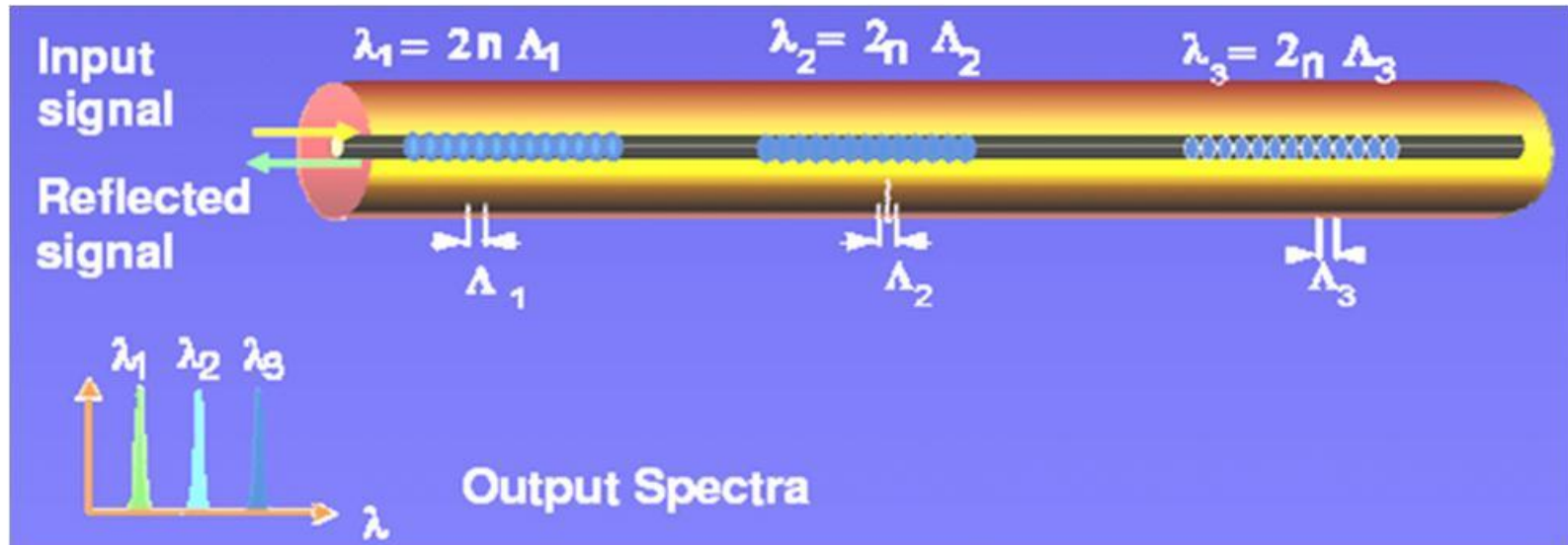
- Optical Sensors – Fiber Bragg Gratings (FBGs)
 - Fiber cores with photo-imprinted FBGs to change refractive index
 - Laser input signals sent through fiber core reflect off FBGs
 - Each FBG sensor has different wave length and spectral operating window band
 - As pressure or temperature changes, reflected wave length changes, providing data



Fiber Bragg Gratings



Fiber Bragg Gratings (cont.)



- Typically can monitor up to +/-2500 microstrain ($\mu\epsilon$)/FBG with up to 40 FBGs written-on or spliced-to each fiber, each FBG having a unique λ_{Bragg}
 - Interrogator scans for and finds each unique- λ_{Bragg} peak
 - Software analyzes each unique- λ_{Bragg} peak and numerically logs its precise λ_{Bragg} value
- Can spread FBG locations over long distances of fiber
- Greatly simplifies cabling, instrumentation, and installation

Fiber Bragg Gratings (cont.)

- Can monitor *many* sensors (>100 in some cases) on *one fiber*
 - Each sensor on fiber is wavelength-specific, providing implicit identification and ability to *multiplex* data.
 - Simplifies cabling and instrumentation:



Cabling and instrumentation for 400
wired strain sensors

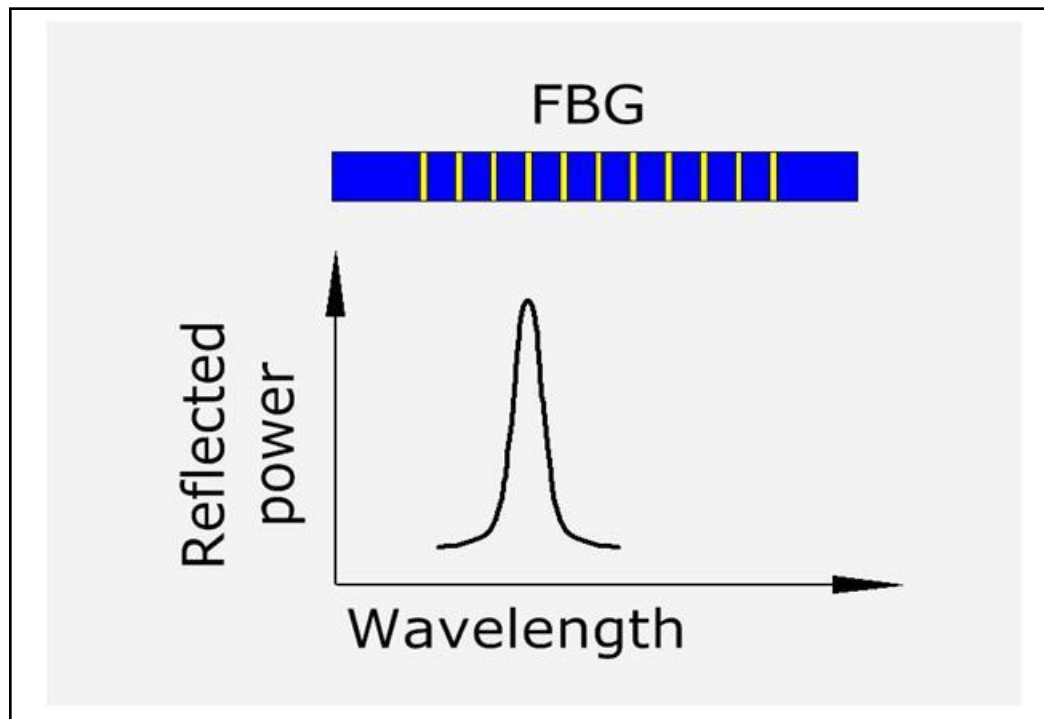


Cabling and instrumentation for \geq
640 multiplexed *fiber-optic* strain
sensors, inside environmental
enclosure with heat exchanger

Fiber Bragg Gratings (cont.)

For FBG strain sensor that is tack-welded/bonded to structure:

- Structure *strain* \rightarrow FBG *stretch/compression*
- FBG stretch/compression $\rightarrow \Lambda$ (FBG period) stretch/compression
- Λ stretch/compression $\rightarrow \lambda_{\text{Bragg}}$ increase/decrease



Fiber Bragg Gratings (cont.)

- Benefits of FBG optical sensors
 - Established, proven technology
 - Fast, accurate, field-reliable
 - Resistant to fatigue and drift
 - Immune to electromagnetic interference
 - Resistant to corrosion, chemicals, water, and lightning
 - Large temperature range (-40 to +150°C)
 - Signals can travel long distances (kilometers)
 - Small, light weight, easy to install
 - Surface mountable or embeddable into structures

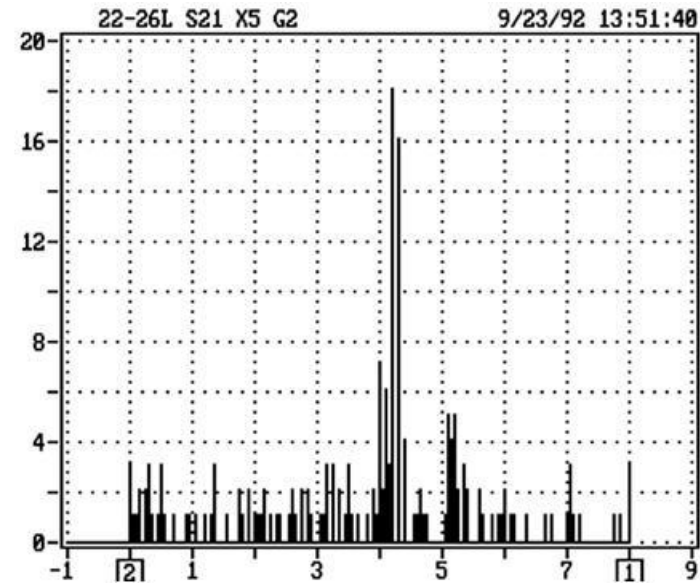


Technology Implementation

- Acoustic Emission (AE) Sensors
 - Detects and locates active, growing defects
 - Totally inspects monitored area for all defects, covering beams, gussets, stringers, and all hidden structural members
 - Only normal bridge traffic and/or wind loads needed
 - Works on both steel and composite bridges
 - Locates cracks by their actual growth
 - Corrosion revealed through reduction in local structural integrity
 - Computerized
 - Quick - results are available in real-time during testing

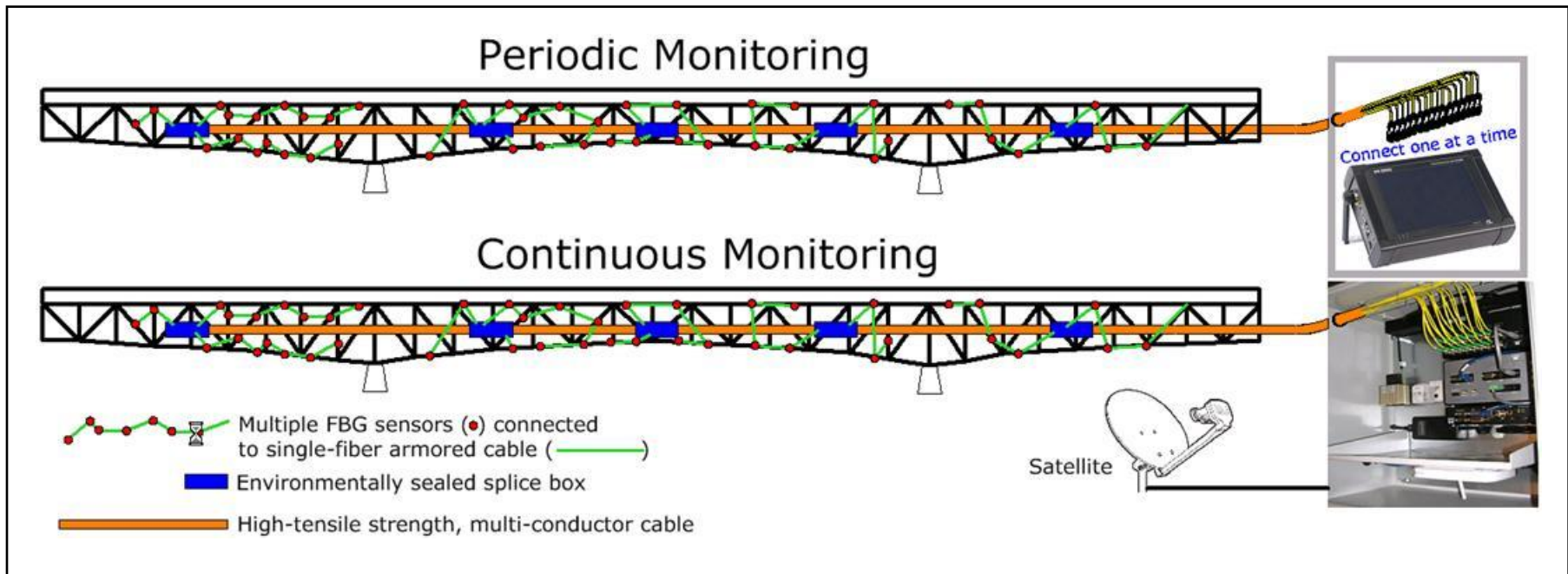


Acoustic Emission Sensors



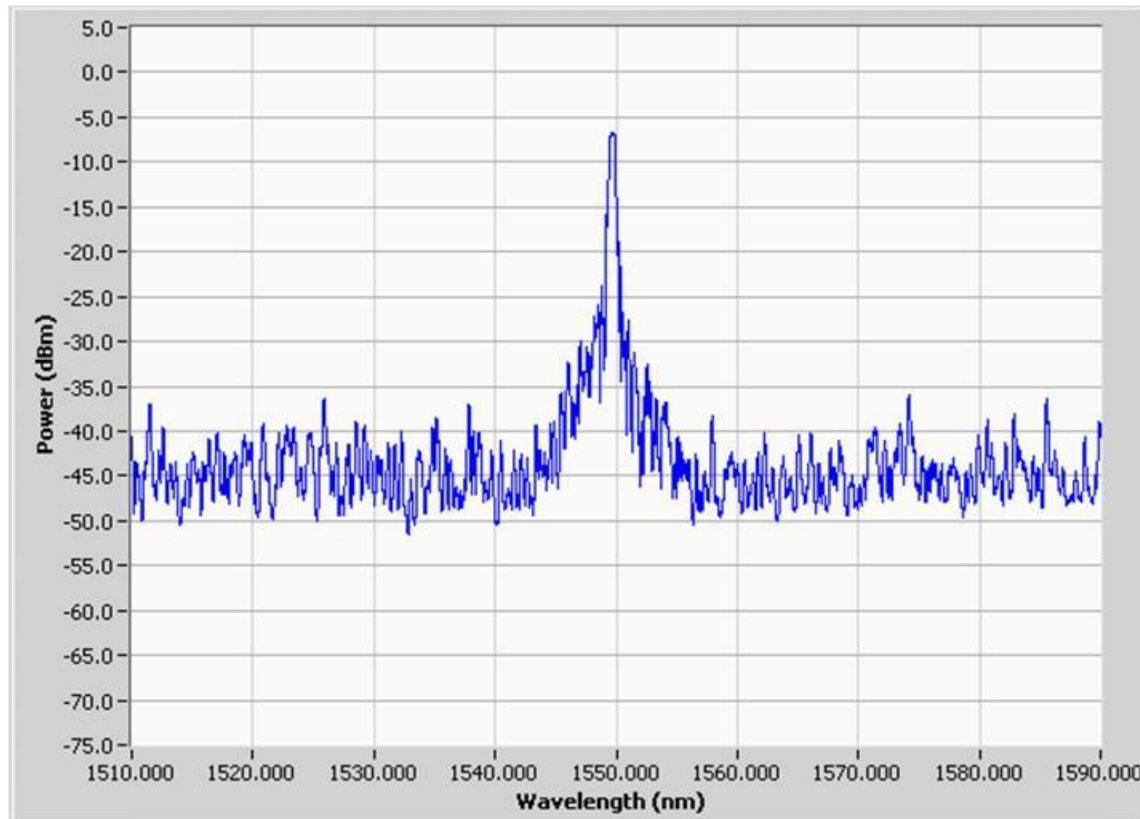
- I-80 Bryte Bend bridge
 - Box-beam design
 - Inappropriate material selection resulted in cracks
 - AE detected 1/16" long fatigue crack, hidden under paint but growing under traffic loading

Technology Implementation - Complete Sensor System



Data Acquisition and Analysis

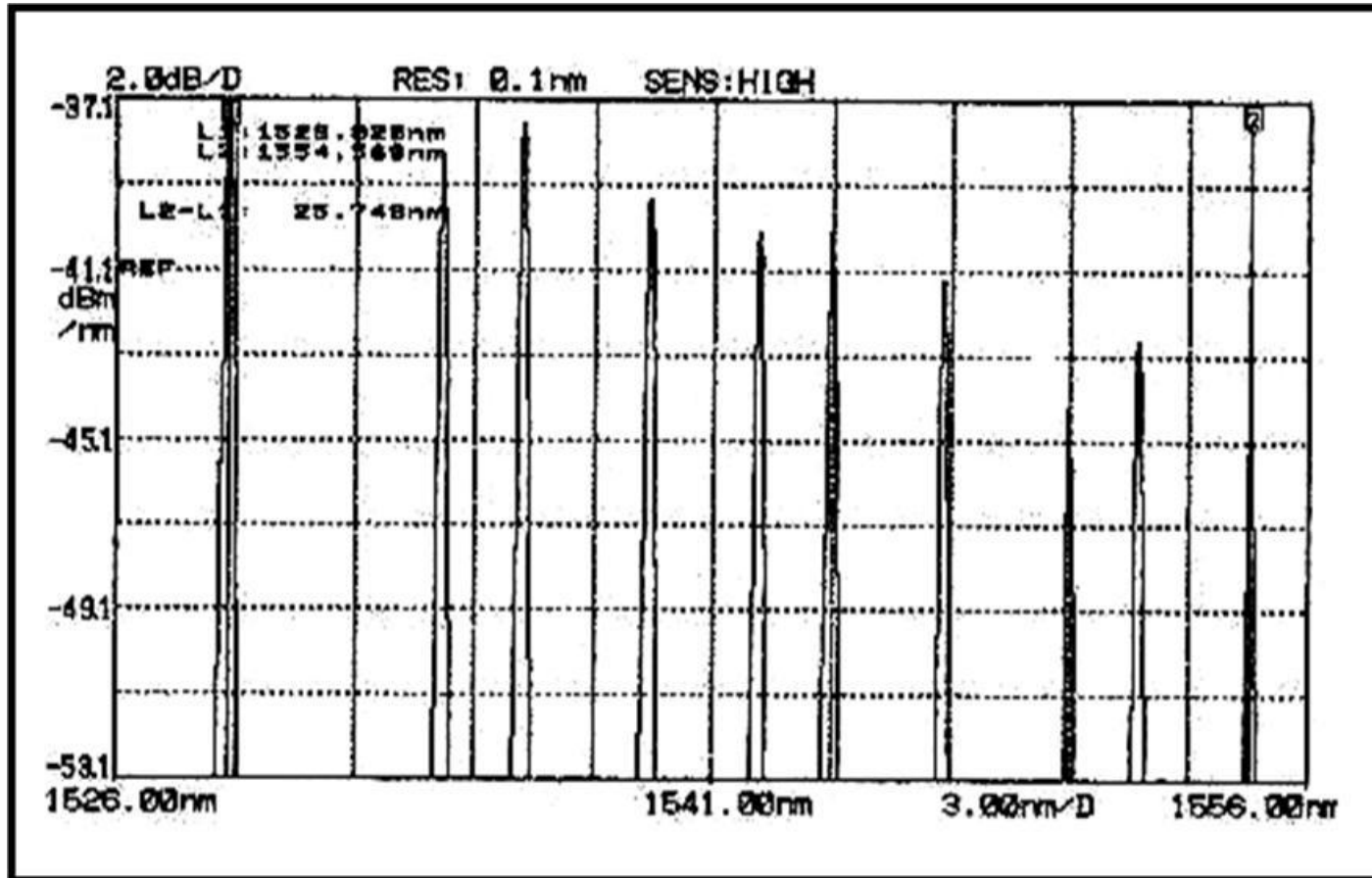
FBG Instrumentation — Typical Scan Results



- Valuable data but must be interpreted!

Data Acquisition and Analysis (cont.)

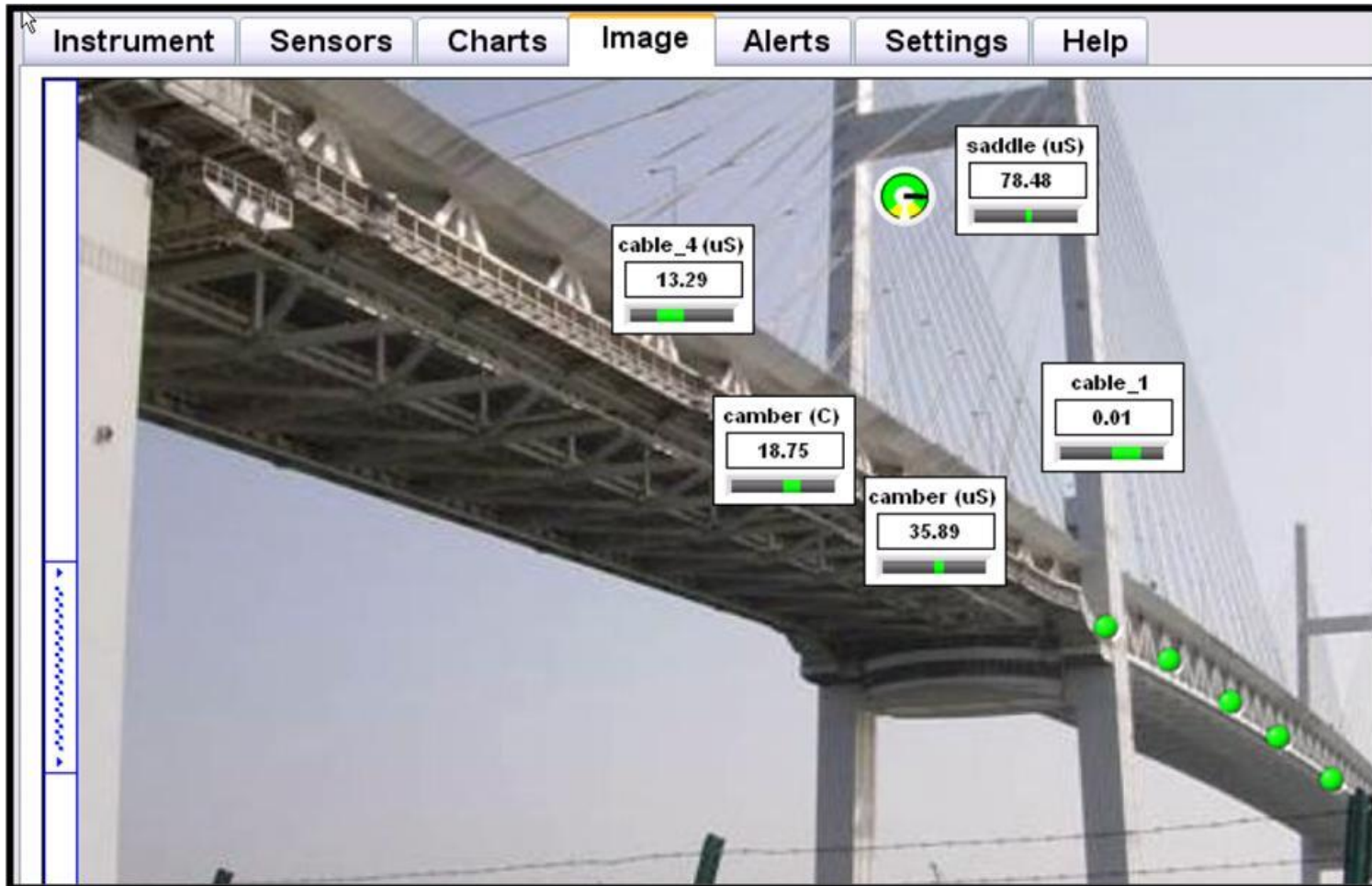
Multi-point λ_{Bragg} peaks as displayed by interrogator



- Valuable data but must be interpreted!

Data Acquisition and Analysis (cont.)

Sensor-location and in-situ graphical data screen



Next Steps/Upcoming Events

- Schedule

MILESTONE CHART	
EVENT	TIME
Project Coordination Meeting	October 2008
Submit Work Plan	October 2008
Kickoff Meetings at Two Subject Bridges	November 2008
Structural Evaluation on Both Bridges	March 2009
Technologies Selected for System	April 2009
Procure Technologies and Assemble System	May 2009
Demonstrate System on Prototype	July 2009
Install System on Two Bridges	August 2009
Confirm Functionality	August 2009
Submit Systems Manual	October 2009
One-Year System Inspection	August 2010
Complete ROI Validation	August 2010
Complete Interim Technical Report	July 2010
Complete Documentation (includes Interim Tech Report, Procurement Specification, etc.)	August 2010



Summary

- The corrosion of steel bridges continues to be a critical infrastructure concern
- A novel sensor system, based on optical FBG sensors but incorporating other unique types of sensors and technologies, is envisioned for the structural health monitoring of these bridges
- The system will provide 24-hour, thorough evaluations of bridge structures, including instantaneous warnings of potential failure spots (visible or not)



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 - Dr. Doug Neale and Mr. Larry Cranford, Mandaree Enterprises Corporation
 - Mr. Kirk Galien and Louisiana DOT
 - Mr. Mitch Carr and Mississippi DOT
 - Mr. Christian Hawkinson and Rock Island DPW
 - Mr. Colby Talbot and C.E.C., Inc.



Thank You!



Questions?



BACKUP SLIDES

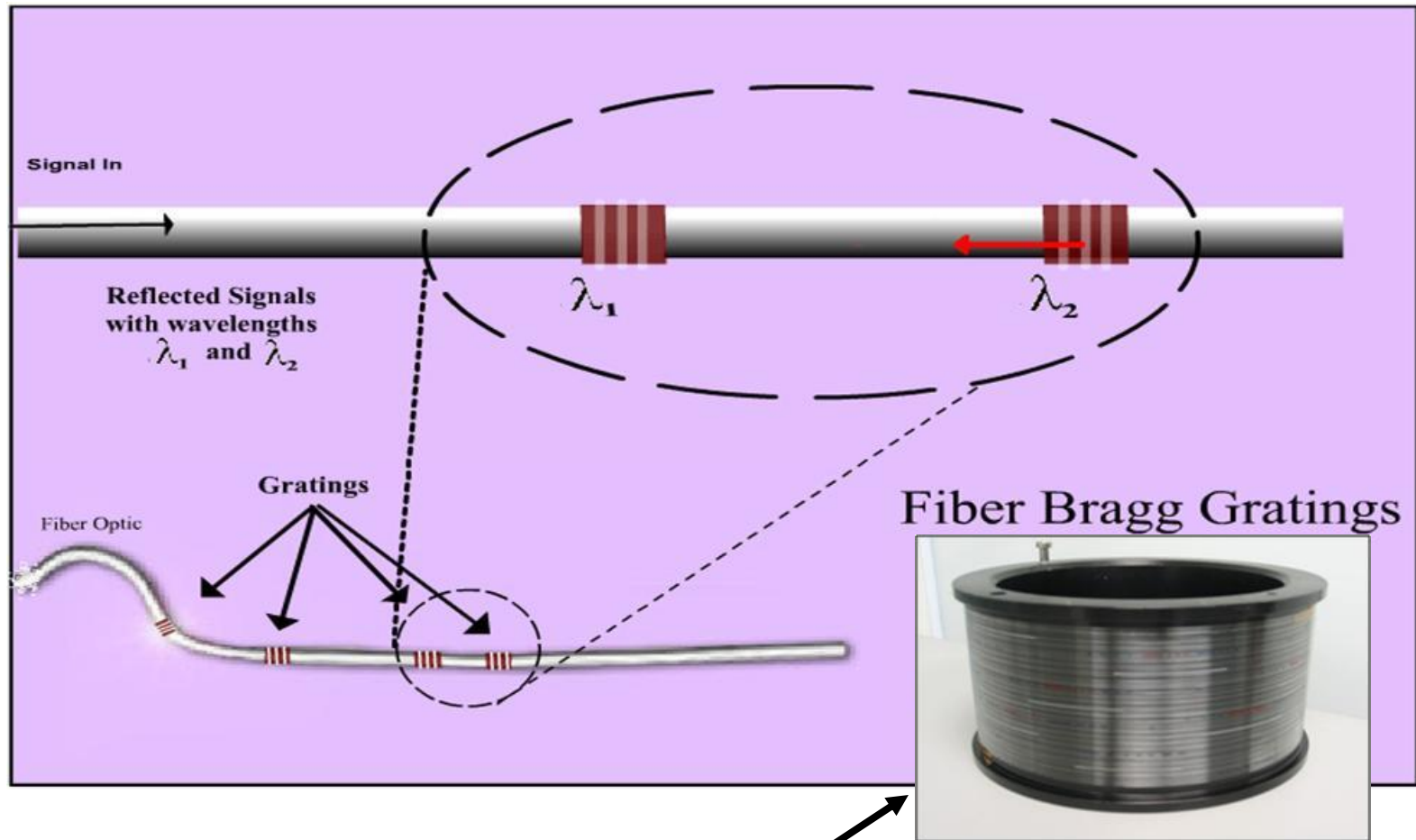


Overall Program Objective (from SOW)

- *“The objectives of this project are to demonstrate and validate state-of-the-art and emerging innovative technology approaches for the remote structural health and corrosion degradation monitoring of steel bridges. The intent of a monitoring system is to greatly reduce the risk of a catastrophic failure by providing advance warning of a growing structural problem caused by corrosion/materials degradation with an opportunity for repair before catastrophic failure. This project will help demonstrate the capabilities of such systems and validate the potential benefits for future possible application by the Army and the rest of the Department of Defense (DoD) on mission critical bridges and similar load bearing structures.”*

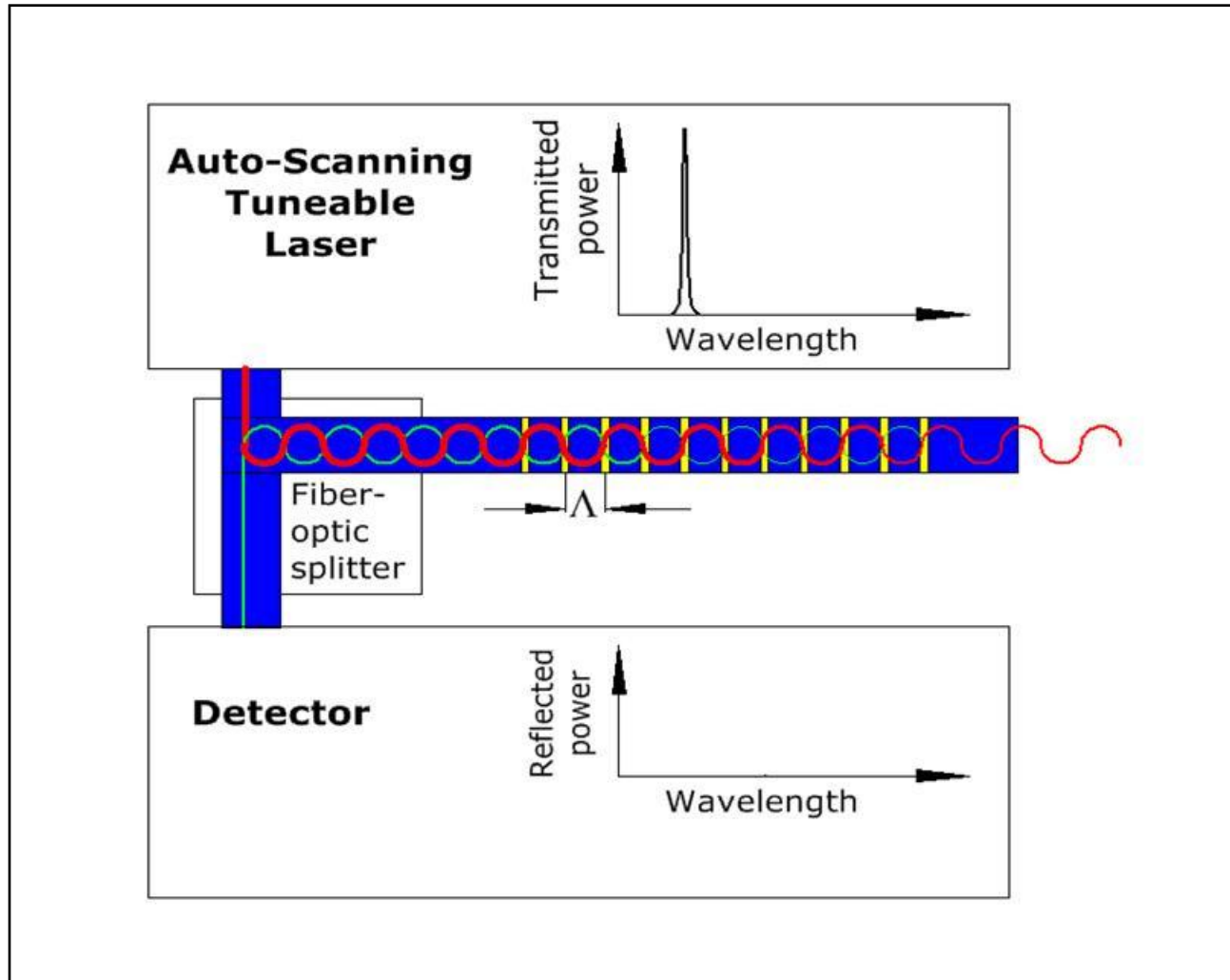


Multi-Point Sensing with One Fiber



Spool containing an FBG array: multitude of FBGs laser-written at discrete points along a single fiber. Can also *splice* many FBGs/sensors into one fiber.

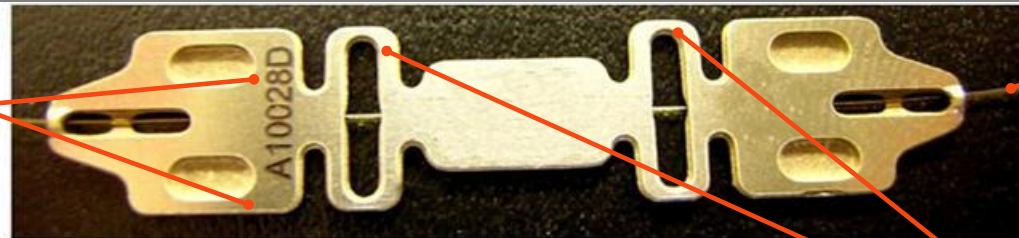
Fiber Bragg Gratings



FBG Sensor Hardware

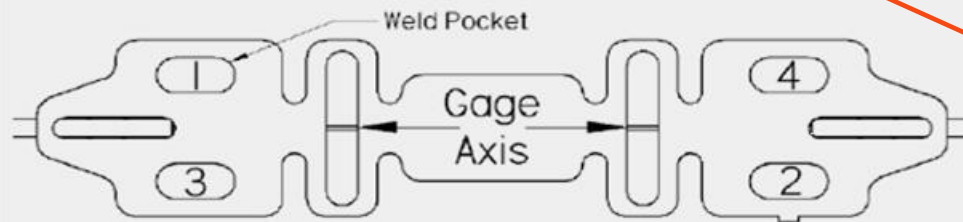
Tack-weldable/bondable FBG strain sensor

Tack-weld
pockets.
Weldable
with
laptop-size,
battery-
powered
welder.



Optical fiber
pigtailed in
protective
braided jackets

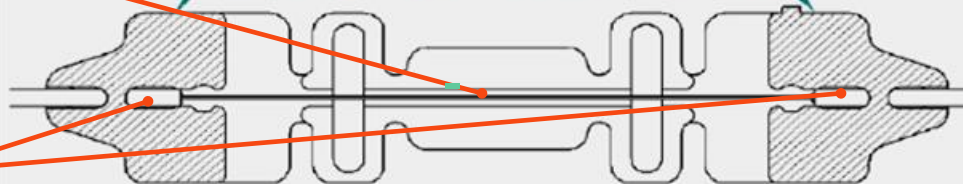
Flexure
springs



Top View

Bonding-Option

Epoxy Application Area



Bottom View

FBG

No-slip/no
creep fiber
connections

Size:
36.5 x
8 x
0.8 mm

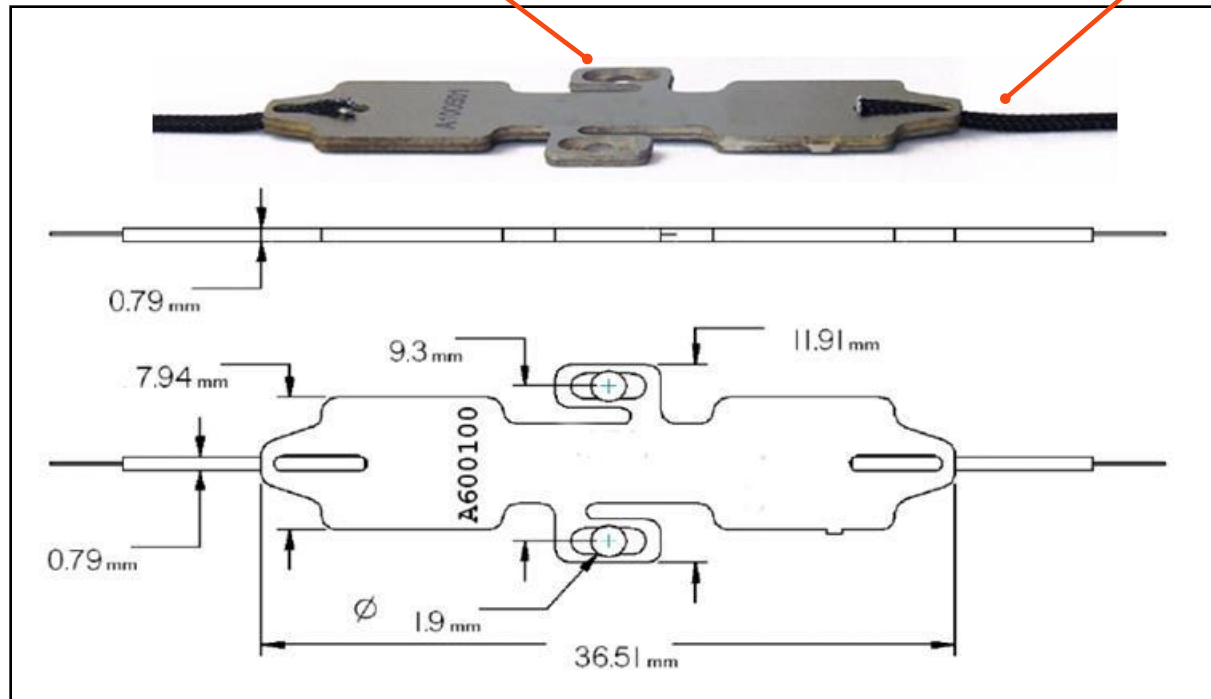
Sensitivity: $\sim 1.2 \mu\epsilon/\text{pm}$. Range: $\pm 2500 \mu\epsilon$. Fatigue life: 10^8 cycles at $\pm 2000 \mu\epsilon$. Temperature limits: -40°C to $+120^\circ\text{C}$. Construction: Stainless steel frame. Fiberglass-braid-protected fiber pigtailed.

FBG Sensor Hardware

Tack-weldable/bondable/screw-mountable FBG temperature sensor

Screw-mount holes & tack-weld pockets. Weldable with laptop-size, battery-powered welder.

Optical fiber in protective braided jacket.



Sensitivity: 28.9 pm/°C. Temperature range: -40 to 120°C. Short-term repeatability $\pm 0.75^\circ\text{C}$ Drift: $\pm 1.0^\circ\text{C}$ at 50°C and 85% RH. Construction: Stainless steel frame. Fiberglass-braid-protected fiber pigtails.

Response of FBG Strain Sensor

Temperature response

More generally, the FBG sensor responds to temperature as well as strain:

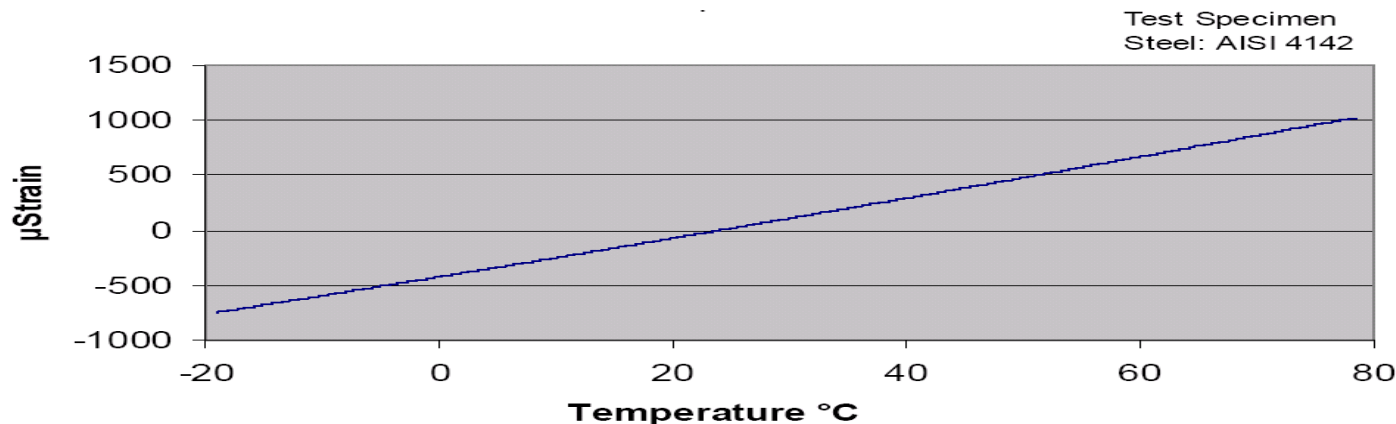
$$\frac{\Delta\lambda_{Bragg}}{\lambda_{Bragg}} = F_G \varepsilon + F_G \Delta T \alpha_{\text{Substrate Expansion}} + \Delta T \alpha_{\text{Refractive Index Change}}$$

Response to *force-induced strain*, ε — the desired variable. (F_G is the gauge factor.)

Response to *true thermal strain* caused by substrate expansion — assuming that the substrate CTE (Coefficient of Thermal Expansion) exceeds the fiber CTE.

Response to *apparent thermal strain*. Cause: change of refractive index (n_d) with temperature. Recall that $\lambda_{Bragg} = 2 \cdot n_d \cdot \Lambda$.

The curve below—for an unstrained FBG strain sensor mounted on steel—illustrates the need for temperature compensation:

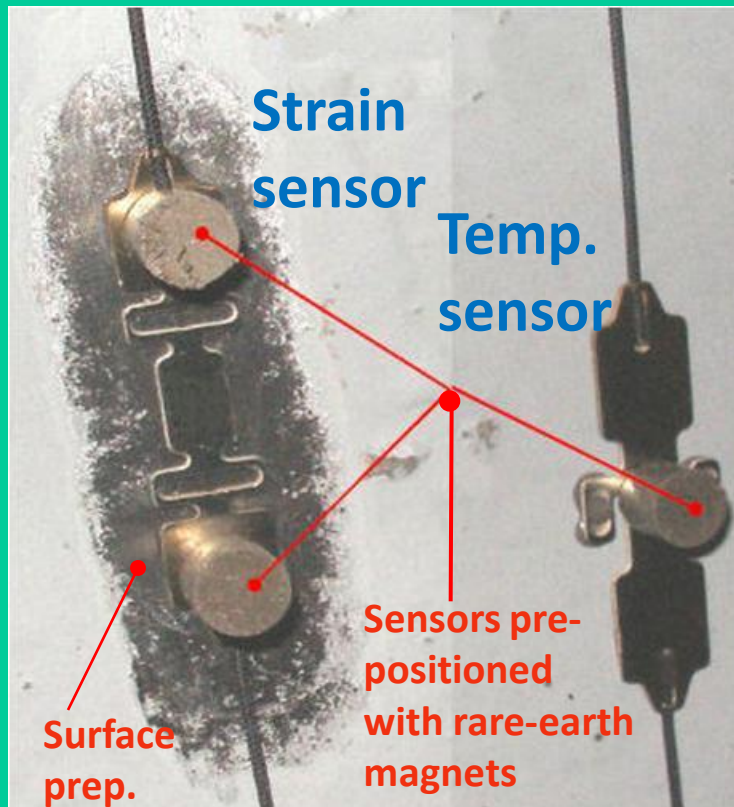


Apparent strain

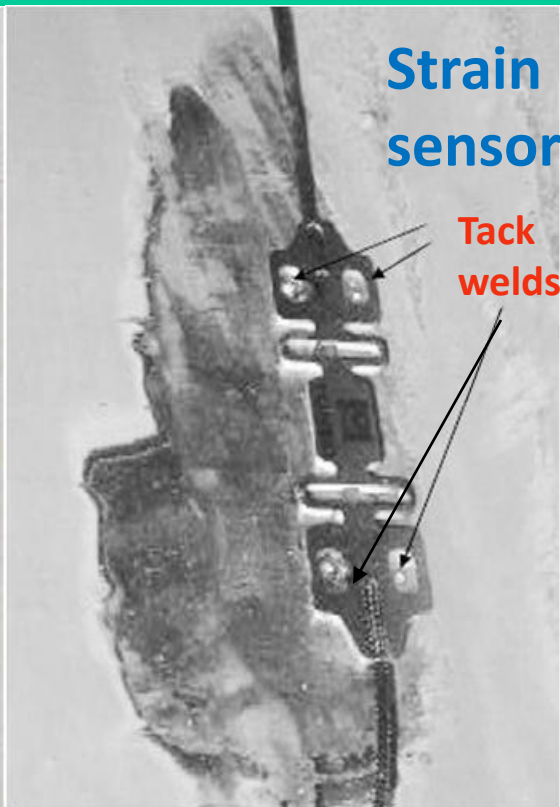
FBG Sensor Hardware

Tack-weldable/bondable FBG strain and temperature sensors: structural installation

Prep & Placement



Welding

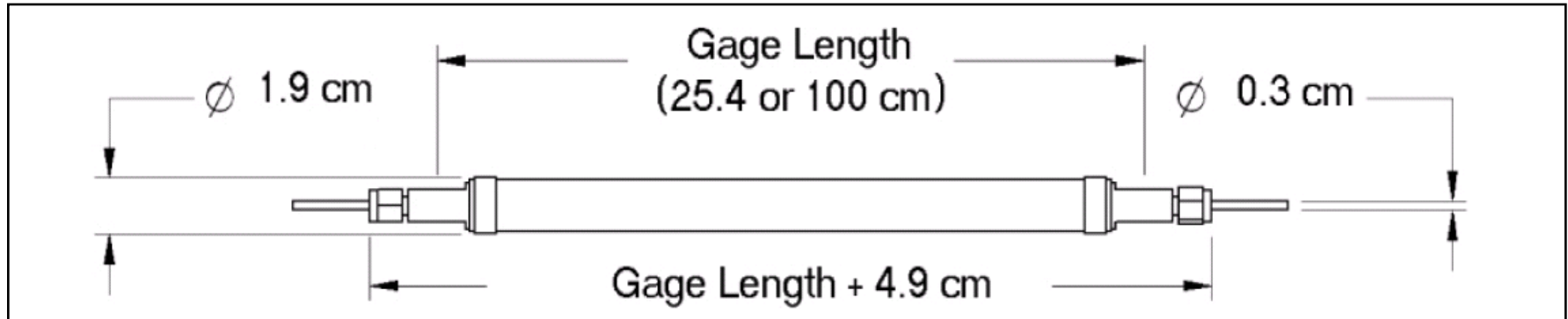


Connection & Encapsulation

- Short pigtails get spliced to **armored** fiber-optic cables.
- Sensor, pigtails, splices, and ends of armored cable get environmentally sealed together with stainless-steel over-patch.

FBG Sensor Hardware

Multi-mountable, environmentally sealed FBG strain sensor

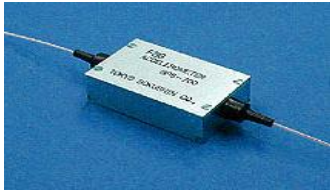


End-mounting options



Sensitivity: $\sim 1 \mu\epsilon$. Accuracy: 0.5%. Range: $2500 \mu\epsilon$. Connection: Armored cable.
Environmental: Stainless steel & Teflon envelope; especially suited for wet environments. Temp. limits: -40C to +80C. Built-in T-compensation FBG.

FBG Sensor Hardware



Accelerometer



Strain meter



Pressure meter



Incline meter



**Relative
Displacement Meter**



Temperature



Fissurometer



**Ocean bottom
seismometer**



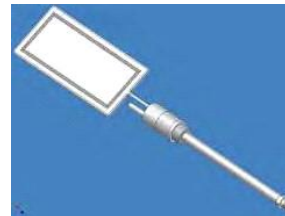
Water Detection



Gas and Humidity



Pressure for Oil Drilling



Load Cell



Land Slide Detection

FBG Sensor Instrumentation

High speed fixed-location FBG interrogator

- Sampling rate as fast as 2000 Hz—with each scan referenced to a stable, zero-temperature-coefficient wavelength standard
- 80 nm standard range (1510 to 1590 nm); 160 nm optional range
- For multiplexed monitoring of 4 fibers—*16 fibers with expansion module*, each fiber potentially containing ≥ 40 FBGs



FBG Sensor Instrumentation

Fixed-location computer

- Interrogator-matched industrial grade PC for data logging, manipulation/analysis, and communication:
- One of two available models



Size: 132 x 267 x 135

FBG Sensor Instrumentation

Moderate speed portable FBG interrogator

- For sampling as fast as 1 ZHz (faster model available soon)
- For multiplexed monitoring of 1 fiber, potentially containing over a hundred FBGs. Complete with integral monitor and pre-installed software

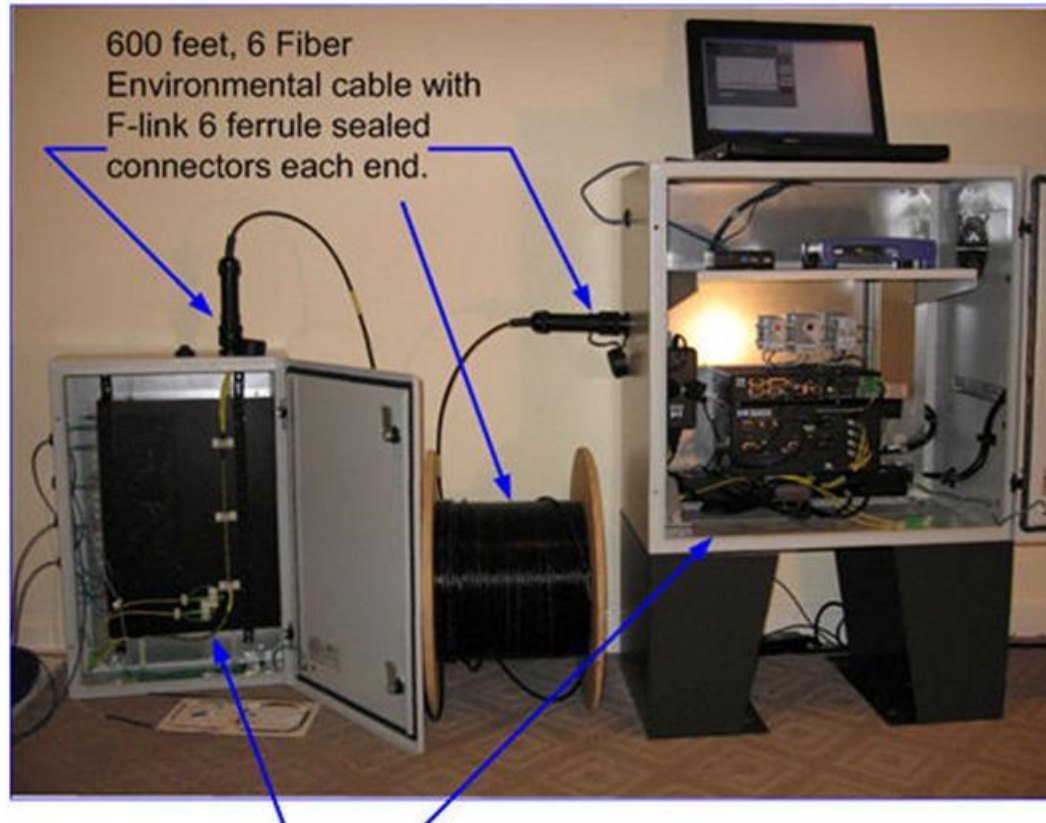


Size:
360 x 275
x
100 mm

Weight:
7.3 kg
(16 lb)

FBG Sensor Instrumentation

Environmentally enclosed *field system* example



**Sm040-016 passive
multiplexer for remote
cable connections**

**Main control cabinet with sm130 high-speed FBG
interrogator, sp130 PC, dual climate control, heat
exchanger, internet switch, satellite modem and optical
/electrical connections**